REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*	2. REPORT DATE	3. DATES COVERED *(From - To)*
9-30-2007	Final	November 2000 -- September 2007

4. TITLE AND SUBTITLE

Mechanistic investigation of small-scale air-sea coupled dynamics using LES
Continued investigation of small-scale air-sea coupled dynamics using CBLAST data

5a. CONTRACT NUMBER

5b. GRANT NUMBER
N00014-01-1-0159

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Yue, Dick K.P.

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Massachusetts Institute of Technoloby
77 Mass Avenue
Cambridge, MA 02139

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
ONR, Code 322MM
875 North Randolph Street, Suite 1425
Arlington, VA 22203

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSORING/MONITORING AGENCY REPORT NUMBER

12. DISTRIBUTION AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT

This study uses direct numerical simulation, large-eddy simulation, and large-wave simulation for both air and ocean turbulent flows with surface waves to investigate the dynamics of coupled air-sea boundary layers at relatively small spatial scales. With extensive simulation in collaboration with measurement, we identify and assess the key transport processes within the atmosphere-ocean wave boundary layer (WBL). This project obtains a physical foundation for the parameterization of the momentum, mass and heat transfer within the atmosphere-ocean WBL.

15. SUBJECT TERMS
Coupled wind-ocean turbulent flows at small scales, surface waves, DNS, LES/LWS, transport process, modeling

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
U	U	U	UU	7	Yue, Dick K.P.
					19b. TELEPONE NUMBER *(Include area code)* 617-253-6823

ONR FINAL REPORT

Contract Information

Contract Number	N00014-01-1-0159
Title of Research	Continued investigation of small-scale air-sea coupled dynamics using CBLAST data
Principal Investigator	Dick K.P. Yue
Organization	Massachusetts Institute of Technology (MIT)

Technical Section

Technical Objectives

Our objective is to obtain a more thorough understanding of the dynamics of coupled air-sea boundary layers at relatively small spatial scales, by performing direct numerical simulation (DNS) and large-eddy simulation (LES) and large-wave simulation (LWS) for both air and ocean turbulent flows with surface waves. With extensive simulation in collaboration with measurement, we aim to identify and assess the key transport processes within the atmosphere-ocean wave boundary layer (WBL). The ultimate goal of this project is to obtain the physical foundation for the characterization and parameterization of the momentum, mass and heat transfer within the atmosphere-ocean WBL.

Technical Approach

For the DNS and LES/LWS of coupled air and ocean turbulent flows, we have developed a suite of high-performance, complementary computational methods. These include: (i) a boundary interface tracking method (BITM) for low wind speeds (<5 m/s); and (ii) an Eulerian interface capturing method (EICM) for moderate to high wind speeds (>5 m/s), where the waves steepen/break. The numerical schemes of BITM are based on boundary-fitted grids and coupled free-surface boundary conditions. The EICM is based on a level set approach. These developments are at the cutting edge of computational free-surface hydrodynamics. Transport of passive scalars in the coupled air-water flow system is implemented. Both the BITM and EICM codes are optimized on parallel computing platforms to provide high-resolution results in a timely manner.

The BITM method solves the incompressible Navier-Stokes equations for both air and water. Free-surface coupled boundary conditions are used at the air-water interface, with the kinematic boundary condition requiring that the interface remains a material surface, and the dynamic boundary condition specifying a stress balance across the interface. The transport of scalars is governed by a convection-diffusion equation. The governing equations are discretized using a pseudo-spectral method in the horizontal directions and a finite-difference scheme in the vertical direction. A second-order fractional-step scheme is used for the time integration of the flow field evolution, the transport of scalars, and the motion of the air-water interface.

In EICM, the air and water together are treated as a system with varying density, viscosity and diffusivity. A continuous scalar (the level set function), which represents the signed distance from the interface, is used to identify each fluid. The fluid motions are governed by the Navier-Stokes equations while the scalar is advected with the flow governed by a Lagrangian-invariant transport equation. A large wave simulation technique is used to model the effects of small surface wave fluctuations on large waves. The governing equations are discretized on an Eulerian grid using a finite-difference scheme.

Work Completed

- *Numerical capabilities*
  We developed high-performance DNS and LES/LWS capability for coupled air-water-wave turbulent flows. The numerical methods of BITM and EICM developed in this project substantially improve the accuracy and physical meaning of the numerical results over existing computational approaches. Optimized codes for high-performance computing (HPC) parallel platforms have been obtained.

- *Physics of air-sea wave coupling*
  We obtained a detailed instantaneous, three-dimensional description of the flow field in the coupled air-water turbulent flow. The datasets obtained from our simulations provide us with a physical basis to gain useful insights into the structures and dynamics of turbulent flows in the vicinity of the air-sea interface. In particular, we identified characteristic vortical structures in the vicinity of the air-water interface to elucidate effects of turbulence coherent structures on transport processes in the air-sea WBL. Micro low-level jets on the air side induced by water motion were discovered, which plays an important role in the transport of passive scalars in the vicinity of the interface. We also obtained a physical understanding of the energy transfer and dissipation process in water and air during wave breaking events.

- *Modeling of coupled air-water dynamics*
  We quantified turbulent kinetic energy (TKE) budget in the vicinity of air-sea interface, to establish the physical basis of meso-scale LES and RANS modeling. We also evaluated enstrophy budget for its parameterization. Of significant importance is that we quantified and completed model assessment for surface renewal process that is essential for air-sea interfacial transport.

Results

In this work, we have developed DNS and LES/LWS capabilities for the coupled air-ocean-wave flow field. A typical simulation result is plotted in Figure 1, which shows the interactions among wind, swell, and ocean current. Such simulation provides important three-dimensional, instantaneous information on the air-sea interactions at the sea surface. Representative quantities including surface pressure distribution, transfer rate of momentum and energy, and vertical structures are shown in Figure 1.

Substantial understanding of the air-sea coupled motion and the transport process within the coupled boundary layers has been obtained via the study of a canonical problem of coupled air-water turbulent Couette flow shown in Figure 2. Through large-scale, high-resolution simulations, we are able to obtain the detailed flow field and scalar concentration distributions. A typical example is shown in the right plot of Figure 2. Based on detailed analyses of the vorticity field, characteristics of vortices have been identified. Vortical structures in the water can be characterized as four categories: hairpin vortices, quasi-streamwise vortices, interface-attached single and paired ("U"-shape) vortices. The first three are illustrated in Figure 2. The coherent vortical structures identified in this study are found to play a significant role in the near-surface transport processes.

After the identification of these instantaneous structures, characterizing and quantifying their effects on near interface transport processes becomes a great challenge. In this study, we employ a variable-interval space-averaging (VISA) technique, which is based on the variable-interval time-averaging (VITA) method developed in experiment. For each type of structures, $O(10^3)$ events are captured with our extensive datasets of simulations. A typical example for the quasi-streamwise vortices is shown in Figure 3. One important discovery from our study is the airside micro low-level jets which are induced by the water motions underneath. The left figure of Figure 3 shows that micro low-level jet is a salient feature in the region to the upper-left of the vortex. Also in that region the convection induced by the vortex makes the thickness of the scalar boundary layer much thinner, as shown in the right figure of Figure 3. As a result, the transfer of the scalar across the interface is greatly enhanced.

Based on the extensive simulation datasets, we obtained important statistics for the modeling and parameterization of atmosphere-ocean coupled boundary layer. In this study we are able to complete the TKE budget in atmosphere-ocean WBL, which is governed by a number of processes. The TKE is produced by the interaction between Reynolds stress and the shear in the mean flow. Meanwhile, it is dissipated by viscosity. In addition to these source and sink processes, TKE is transported among different flow regions by pressure fluctuations and velocity fluctuations. At regions where the TKE varies abruptly, viscous diffusion also contributes to the TKE. Figure 4 shows that the TKE production is large near the interface. The sharp decrease at the interface is caused by the reduction of Reynolds stress there. Viscous diffusion is only significant very close to the interface. Transport due to turbulence velocity fluctuations transports TKE from the bulk region of the air to the near-surface region. On the waterside, turbulence transport removes part of TKE from the near-surface region and put it at the deep region. Dissipation increases towards the interface in the air and reaches a maximum at the interface, behaving like near a solid wall. On the waterside, as the interface is approached, dissipation decreases first and then increases. The results obtained here will allow us to develop advanced closure models needed, for example, in larger scale and coarser grid simulations such as those used in meso-scale LES and RANS computations.

We also obtained valuable statistics of surface renewal, which is the most important interfacial transport process. Of significant importance is that we develop a novel Lagrangian and Eulerian approach for quantifying ages of fluid surface elements. Figure 5 shows the probability density obtained from our direct numerical simulation. Various theoretical results, including exponential, Gamma, normal, and lognormal distributions are examined. It is found that the distribution of surface age is not Gaussian. The exponential distribution based on the assumption of random surface replacement, which is widely used in the literature, does not capture the entire process of the surface renewal. For young surface elements, the lognormal is a good fit, while for old elements the Gamma curve works better. Considering that the majority of surface flux occurs right after surface renewal, we conclude that the surface age distribution can be best described by the lognormal. This result establishes a physical basis for the parameterization of scalar transport at the air-sea interface.

Impact/Application

This study aims to obtain a fundamental understanding of the air-sea wave coupling dynamics at small scales at low wind speeds. Our work is a small yet essential part of an overall coordinated effort involving field experimentalists, air-sea modelers, and physical oceanographers to obtain improved physics-based parameterizations for air-sea interactions. Our numerical simulations provide detailed descriptions of the air-sea-wave boundary layer at small scales, and a physical basis for the modeling and parameterization of transport process within the atmosphere-ocean wave boundary layer. The simulations also provide comparison and cross-validation with field measurements. Finally, our numerical framework can be used as a powerful tool to help the interpretation and syntheses of field data, and parameterization of WBL transport process for the coupled air-ocean WBL modeling.

Publications

1. Shen, L. & Yue, D.K.P., "Structure of vertical mixing layers near a free surface," *Bulletin American Physical Society*, Vol. 46, 2001
2. Yue, D.K.P & Shen, L., "Mechanisms of passive-scalar transport near a free surface," *Bulletin American Physical Society*, Vol. 46, 2001
3. Hendrickson, K., Shen, L. & Yue, D.K.P., "Coupled air-water interface and energy dynamics in steep breaking water waves using a level-set method," *Bulletin American Physical Society*, Vol. 47, 2002
4. Shen, L., Zhang, X., Triantafyllou, M.S. & Yue, D.K.P., "Turbulent flow over a flexible wall undergoing a streamwise traveling wave motion," *Journal of Fluid Mechanics,* Vol. 484, 2003.
5. Shen, L., Yue, D.K.P., & Triantafyllou, G.S., "Effect of surfactants on free-surface turbulent flows. Part 1. Statistics and vortex structures," *Bulletin American Physical Society*, Vol. 48, 2003
6. Triantafyllou, G.S., Shen, L. & Yue, D.K.P., "Effect of surfactants on free-surface turbulent flows. Part 2. Structure of surface layers," *Bulletin American Physical Society*, Vol. 48, 2003
7. Liu, S., Hendrickson, K., Dong, X., Shen, L. & Yue, D.K.P., "Numerical investigation of coupled boundary layers air-sea transfer (CBLAST) at small scales," *Proceedings of 16th Symposium on Boundary Layer*, 2004
8. Shen, L., Triantafyllou, G.S. & Yue, D.K.P., "Effects of surfactants on free-surface turbulent flows," *Journal of Fluid Mechanics,* Vol. 506, 2004.
9. Hendrickson, K., Liu, S., Shen, L. & Yue, D.K.P., "Numerical investigation of coupled air-water turbulent boundary layers at small scales," *EOS Transactions*, Vol. 84(52), 2004
10. Shen, L., Liu, S. & Yue, D.K.P., "Mechanisms of air-sea interactions at small scales," *Proceedings of Civil Engineering in the Ocean VI*, 2005.
11. Hendrickson, K. & Yue, D.K.P., "Navier-Stokes Simulations of Unsteady Small-Scale Breaking Waves with a Coupled Air-Water Interface," *Proceedings of 26th Symposium on Naval Hydrodynamics*, 2006
12. Shen, L. & Yue, D.K.P., "Modeling the relationships between flow statistics and structures at the coupled air-ocean interface ," *Oceanography*, Vol. 19(1), 2006
13. Connell B.S.H. & Yue D.K.P., "Flapping dynamics of a flag in a uniform stream," *Journal of Fluid Mechanics,* Vol. 581, 2007.
14. Edson, J.B. et al., "The coupled boundary layers and air-sea transfer experiment in low winds (CBLAST-LOW)". *Bulletin of the American Meteorology Society,* Vol. 88(3), 341-356, 2007

Student Graduated

4

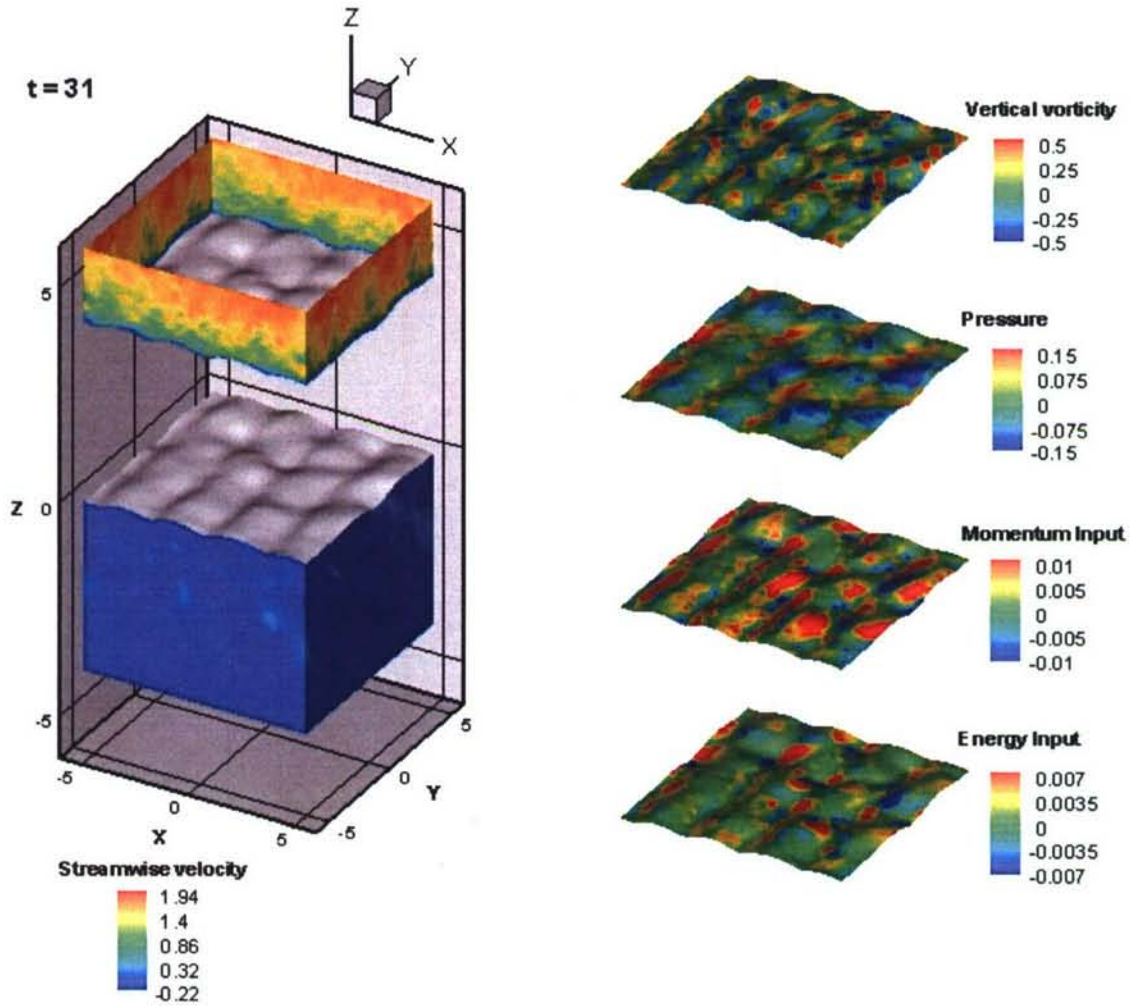

Figure 1. Interaction among wind, swell, and underwater current. Plotted on the left are surface wave profile and contours of air and water velocity in the direction of wave propagation. The contours on the right are surface distributions of vertical vorticity, pressure, momentum and energy inputs from the air to water, respectively.

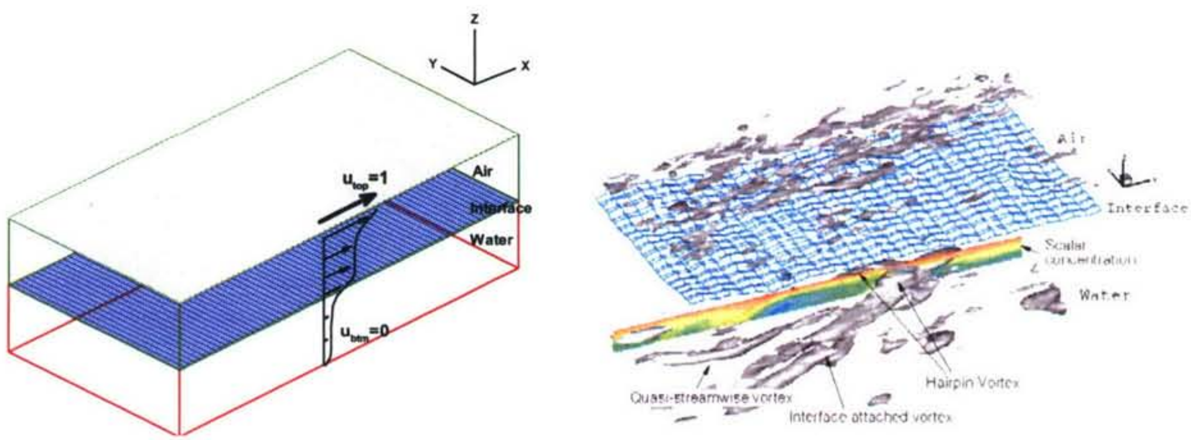

Figure 2. Left: schematics of air-water coupled Couette flow. Right: instantaneous vortical structures in the air and water turbulent flow field, and instantaneous scalar concentration contours.

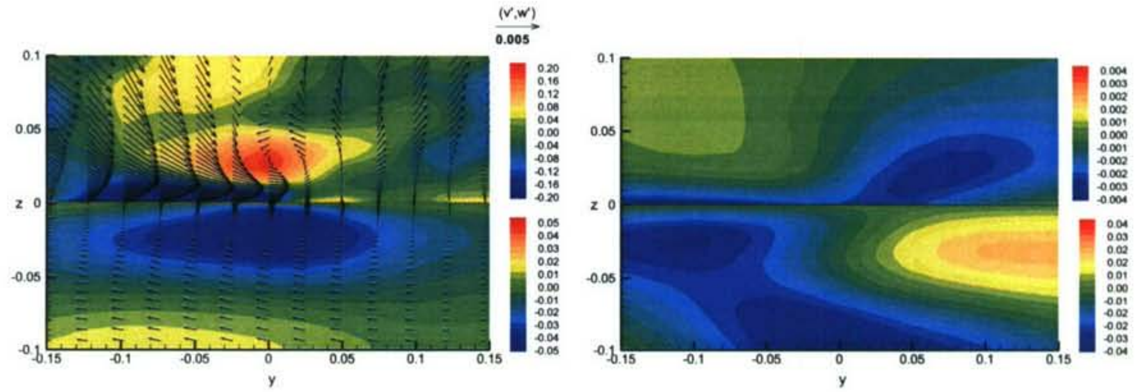

Figure 3. Quasi-streamwise vortex on the waterside and the induced mirror vortex and micro low-level jet on the airside, and their effects on passive scalar transport near the interface. Shown in the left figure are contours of vorticity component and fluctuation velocity vectors. Shown in the right figure are contours of scalar concentration fluctuations.

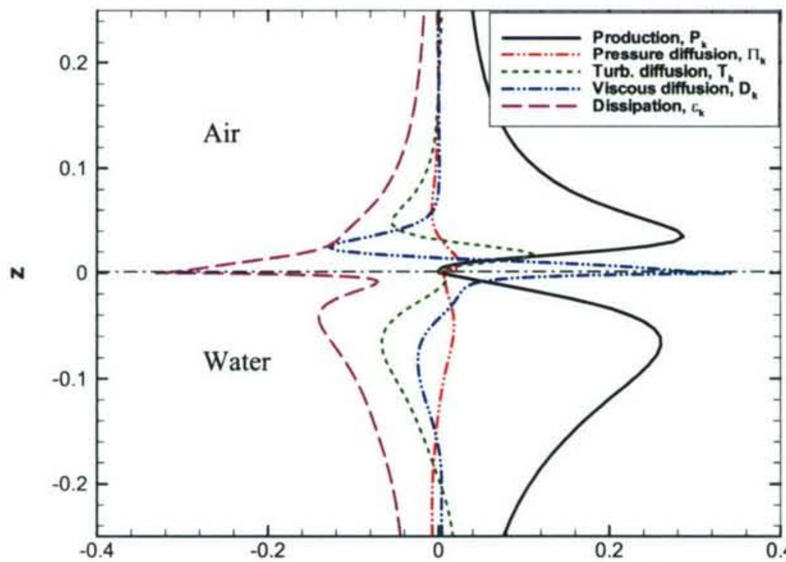

Figure 4. Profiles of turbulence kinetic energy budget terms in the coupled air-water boundary layer.

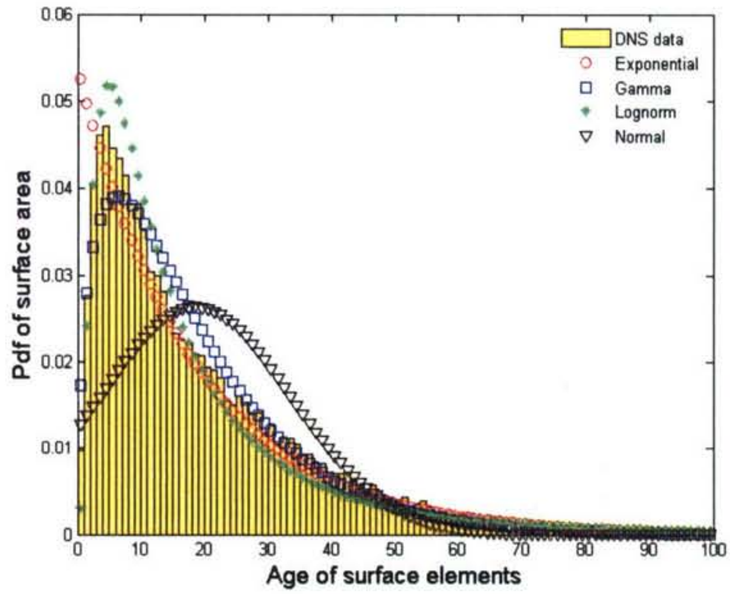

Figure 5. Probability distribution of surface element age with respect to the surface renewal process. Histogram is obtained from simulation data. Curve fittings are exponential, Gamma, lognormal, and normal, respectively.